NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

December 21, 2005

MATERIALS LABORATORY STUDY   Report No. 05-124

A. ACCIDENT

Place	:	Wilmer, Texas
Date	:	September 23, 2005
Vehicle	:	MCI Motorcoach
NTSB No.	:	HWY05MH035
Investigator	:	James E. Henderson, RPH-30

B. COMPONENTS EXAMINED

Medical oxygen cylinder assemblies.

C. DETAILS OF THE EXAMINATION

In this study, the gage pressure of oxygen in medical oxygen cylinder assemblies such as cylinder assemblies recovered from the accident motorcoach was calculated as a function of temperature using the ideal gas law. Also, the resulting Mises effective stresses in the cylinder wall were calculated using equations for a thin-walled pressure vessel[1]. Results of these calculations are shown in figure 1. The Mises effective stress was then compared to the tensile yield stress for the cylinder material at the corresponding temperatures, and these results also are shown in figure 1.

Calculation Methods

Calculations of cylinder pressure were derived from the ideal gas law adjusted to account for compressibility of oxygen using the following equation,

$$P_a = \frac{ZnRT_a}{V} \quad , \tag{1}$$

where P_a is the absolute pressure, Z is the compressibility factor for oxygen, n is the number of moles of oxygen in the cylinder, R is the universal gas constant, T_a is the absolute temperature, and V is the volume of the cylinder. The compressibility factor of

[1] The specified nominal internal radius to wall thickness ratio for the oxygen cylinders is 9.94, just below the accepted approximate minimum of 10 for use of thin walled equations. Nevertheless, to simplify the calculations, thin walled equations were used.

oxygen as a function of temperature and pressure was determined using linear interpolation of values listed in *Chemical Engineers' Handbook, Fifth Edition*.[2]

Absolute pressure for a cylinder was calculated as a function of absolute temperature using the following equation assuming a constant volume and molar content for the cylinder,

$$P_{a2} = \frac{P_{a1} \cdot T_{a2} Z_2}{T_{a1} Z_1} \ , \qquad (2)$$

where the initial and final absolute pressures, absolute temperatures, and compression factors for the gas in the cylinder are represented by subscripts 1 and 2, respectively. For a full cylinder, it was assumed the cylinders were filled to an initial gauge pressure of 2,015 pounds per square inch at a temperature of 70 degrees Fahrenheit. Adjusting for atmospheric pressure and converting temperature to an absolute scale, the initial absolute pressure and absolute temperature for a full cylinder assembly was assumed to be 2,030 pounds per square inch and 294 degrees Kelvin.

Additionally, absolute pressure for a part full cylinder was calculated as a function of absolute temperature using equation 1. For the part full cylinders, the initial gage pressures at 70 degrees Fahrenheit were assumed to be some fraction of the full gage pressure of 2,015 pounds per square inch. For example, a cylinder that was 50 percent full would have an initial gage pressure of 1,008 pounds per square inch at 70 degrees Fahrenheit. Adjusting for atmospheric pressure and converting temperature to an absolute scale, the initial absolute pressure and absolute temperature for a 50-percent full cylinder was assumed to be 1,022 pounds per square inch and 294 degrees Kelvin.

Once the absolute pressure for the final gas state, P_{a2}, was determined using equation 2, the gage pressure for the cylinder in the final gas state, P_{g2}, was determined by subtracting the atmospheric pressure from the absolute pressure. The gage pressure was calculated for cylinders with contents ranging from 10 percent of full to full and for temperatures ranging from room temperature to 800 degrees Fahrenheit. The relationship between temperature and gage pressure for full and part full cylinders is shown by the positive-sloping lines in figure 1 as read using the vertical axis at the right.

The approximate stress in the cylinder wall for a given gage pressure, P_{g2}, was calculated using equations for a thin-walled pressure vessel. The hoop stress, σ_h, was calculated using the following equation,

$$\sigma_h = \frac{P_{g2} D}{2t} \ , \qquad (2)$$

[2] *Chemical Engineers' Handbook, Fifth Ed.*, Ed. by R. H. Perry and C. H. Chilton, McGraw-Hill Book Co. (1973) pp. 3-108, Table 3-166.

where D is the nominal internal diameter and t is the nominal wall thickness. The longitudinal stress, σ_l, was calculated using the following equation,

$$\sigma_l = \frac{P_{g2} D^2}{\left(4tD + 4t^2\right)}. \tag{3}$$

In this study, the nominal internal diameter of the cylinders was 3.975 inches, and the nominal wall thickness was 0.2 inch.

The effective stress, $\bar{\sigma}$, for use with the von Mises yield criterion was calculated from the hoop and longitudinal stresses using the following equation,

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{\left(\sigma_h - \sigma_l\right)^2 + {\sigma_h}^2 + {\sigma_l}^2}. \tag{4}$$

The relationship between temperature and the effective stress for full and part full cylinders is shown by the positive-sloping lines in figure 1 as read using the vertical axis at the left. Using the von Mises yield criterion, yielding occurs when the effective stress is equal to the tensile yield strength.

The tensile yield strength of aluminum alloy 6061-T6 is also shown as a function of temperature in figure 1. In figure 1, the tensile yield strength is presented in terms of effective stress, which is equal to the tensile stress in uniaxial tension. Strength data for the 6061-T6 alloy tested at temperature after a ½-hour exposure at temperature was obtained from the *Aerospace Structural Metals Handbook*.[3]

Discussion

As can be seen in figure 1, the line for the effective stress of a full cylinder intersects the green line for the yield strength at approximately 375 degrees Fahrenheit and at a gauge pressure of approximately 3,640 pounds per square inch, indicating that at temperature equilibrium between the cylinder wall and the gas, this is the temperature and gauge pressure at which a full cylinder would yield from the internal pressure. Part full cylinders yield at higher temperatures and lower gauge pressures. A 78 percent full cylinder yields at approximately 440 degrees Fahrenheit and at a gauge pressure of approximately 3,000 pounds per square inch.

Some of the valves on cylinder assemblies from the accident were Sherwood CG-4 style valves, which include a pressure relief device (PRD). According to literature obtained from Sherwood, the specified gage pressure range for activating the CG-4 style Sherwood valve PRD at 160 degrees Fahrenheit is 3,025 pounds per square inch to 3,360 pounds per square inch. This study indicates that the gage pressure of a full cylinder would reach

[3] *Aerospace Structural Metals Handbook*, Ed. by W.F. Brown, H. Mindlin, and C.Y. Ho, Cindas/USAF CRDA Handbooks, Purdue University (1995) section 3206, figure 3.0315.

3,000 pounds per square inch after heating to 260 degrees Fahrenheit and would reach 3,300 pounds per square inch after heating to 315 degrees Fahrenheit. For cylinders less than 78 percent full, the gage pressure upon heating would not reach 3,000 pounds per square inch before the cylinder yielded.

We can also consider the effects of non-equilibrium conditions on the results shown in figure 1. Regarding cylinders that are heated from external heat, particularly those that are also heated locally, the cylinder wall temperature in local areas could be considerably higher than the average internal gas temperature. To explore the effect of this non-equilibrium case, the temperature denoted in the independent axis of figure 1 could be considered the cylinder wall temperature, and the gas temperature would be some temperature between room temperature and the cylinder wall temperature depending on the degree to which the cylinder is out of equilibrium. In effect, the positive-sloping lines in figure 1 would have the same plotted point at room temperature, but would have a slope greater than zero but less than that shown in figure 1 depending on the degree to which the cylinder is out of equilibrium. Thus for non-equilibrium conditions with external heat, the positive-sloping lines shown in figure 1 represent an upper bound for the gas pressure and cylinder wall stress at a given external temperature. As such, for full or part full cylinders heated from an external heat source, the temperature at the intersection of each positive-sloping line and the green line in figure 1 would represent a minimum external cylinder wall temperature at which yielding would be expected for cylinders initially filled to the level indicated for that particular positive-sloping line. Therefore, under some non-equilibrium conditions, it would be possible for even a full cylinder to yield before the pressure was released by the PRD.

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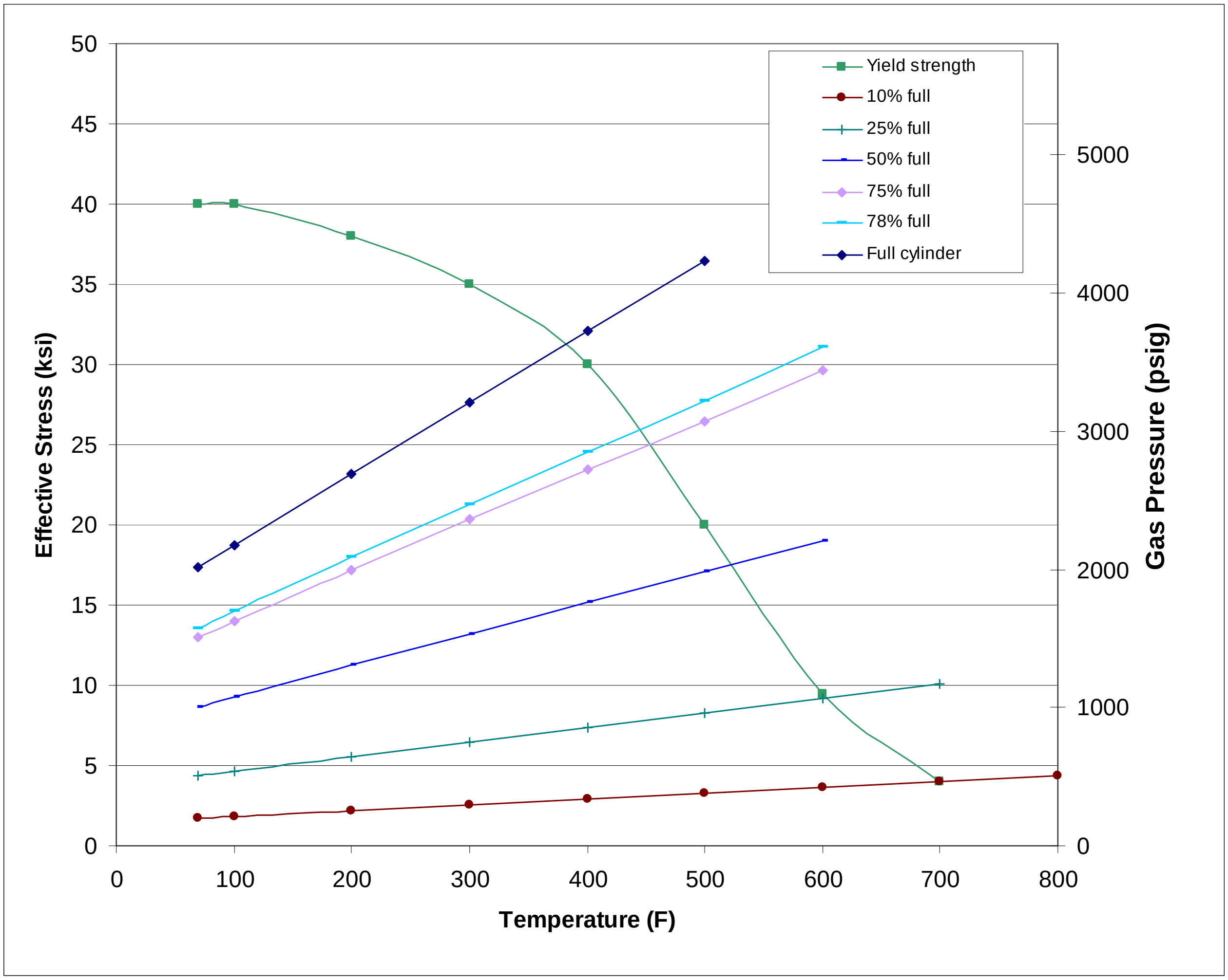

Figure 1. Chart showing the relationship between temperature and the effective stress in a cylinder wall for a full cylinder filled to an initial gage pressure of 2015 at 70 degrees Fahrenheit and for part full cylinders filled to a fraction of 2015 pounds per square inch at 70 degrees Fahrenheit. For the cylinder geometry used in this study, gauge pressures shown on the vertical axis at the right correspond to the effective stresses in the wall shown on the vertical axis at the left. Tensile yield strengths and ultimate strengths for the cylinder material are shown in terms of effective stress as they vary with temperature. Cylinder yielding would be expected at combinations of temperature and pressure above and to the right of the green line.